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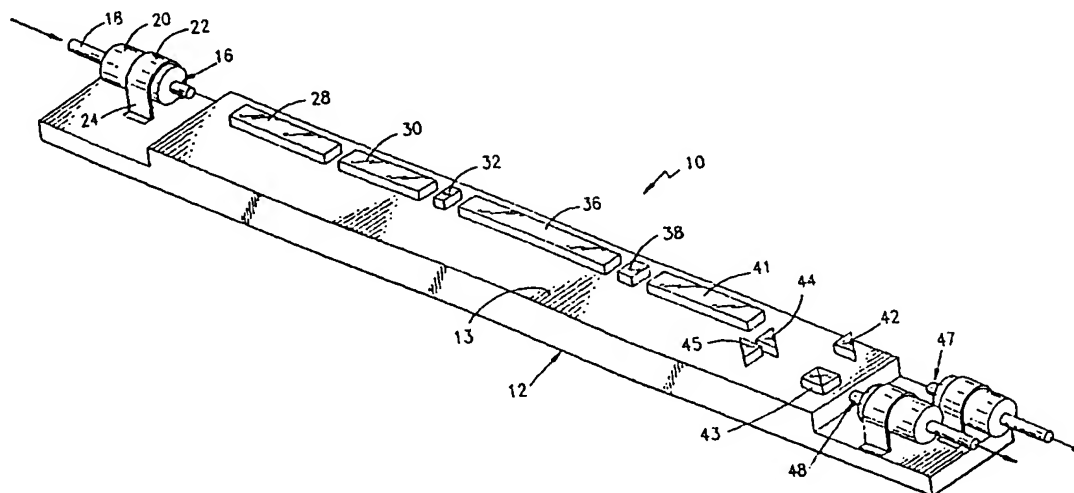
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(54) Title: INTERLEAVING OPTICAL FILTER



(57) Abstract: An optical signal filter for providing a periodic transfer function in transmitting signals within a selected bandwidth, by which passbands are interleaved into groups of separate outputs. The filter employs the transmissivity characteristic of birefringent crystals in conjunction with splitting the input beam into orthogonal and separate components, while compensating for temperature variations by pairing crystals of different types. The transmissivity functions are independent of the polarization of the input beam, and are shaped to flatten transmissivity peaks by the use of cascaded stages of birefringent crystal pairs.

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INTERLEAVING OPTICAL FILTER

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Field of the Invention

This invention relates to wavelength division multiplexed (DWDM) systems used in optical fiber communications, and more particularly to optical signal filters which separate a WDM channel stream into groups of channels on separate fibers.

Background of the Invention

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Narrow band optical filters are essential in wavelength division (WDM) communication systems in order to process signals at different precisely spaced wavelengths. Low insertion loss, flat top filter response, sharp cutoff, and the ability to scale to high channel counts and dense channel spacing are all critical parameters. An interleaving filter is a device or subsystem which can separate multiple channels in a WDM transmission into groups. A 1x2 interleaving filter divides a WDM channel stream, periodically spaced in optical frequency, in a manner such that every other channel is launched into one of two separate fibers. More generally a 1xN interleaving filter, separates every Nth channel into one of N fibers.

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The interleaving function, more broadly speaking, includes establishing a periodic transmissivity characteristic within a given wider frequency band, so that there is virtually lossless transmission within incrementally spaced frequency channels, and in effect full signal rejection between the channels. Preferably, the transmissive pass bands are shaped with flat top response, so that laser wavelength shifts and other variations within the pass bands can be tolerated, thus reducing the stringency of performance specifications imposed on such active elements. Therefore, in multiplexing, channel spacings can be reduced with improved performance, while in demultiplexing closely spaced channels can be separated without requiring prohibitively precise individual components, such as add/drop filters. In demultiplexing,

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interleaving filters can also serve to reduce the component counts and serial insertion losses, because they separate signals in parallel fashion and can be cascaded to divide channels into a number of smaller groups before wavelength selective devices are used to add or drop individual wavelength signals.

5 The most common approach to interleaving filter design is based upon using unbalanced Mach-Zender interferometers. These are adequately responsive but are large, costly units that are difficult to adapt to many system requirements. In addition, they are subject to inherent instability problems that require extra measures to overcome. Thin film 200 GHz filters are now being offered, but thin films require costly and precise processes. Other periodic optical transmission
10 functions are known, such as those exhibited by birefringent crystals, as delineated in detail by Yeh and Yariv in "Optical Waves in Crystals", John Wiley and Sons (1983). As the authors explain, a birefringent element sandwiched between parallel polarizers has a transmission characteristic that is periodic in optical frequency, and effectively without loss at transmissive peaks. Much analytical work, of both theoretical and practical natures has been directed to using
15 the properties of birefringent crystals. In 1964, for example, Harris et al proposed a procedure for the synthesis of optical networks in an article in the Journal of the Optical Society of America, Vol. 54, No. 10 (Oct. 1964), pp. 1267-1279, entitled "Optical Network Synthesis Using Birefringent Crystals". This article treats some of the considerations fundamental to synthesizing specific transfer functions using a series of birefringent crystals between entry and exit polarizers.
20 Subsequently, Kimura et al discussed a technique for reducing thermally induced variations in an article entitled "Temperature Compensation of Birefringent Optical Filters", in the Proceedings of the IEEE, August 1971, pp. 1271-2. They disclosed that if the signs of the birefringence of two different crystals are opposite, the retardation of the series is less dependent on temperature. Although the intended purpose of the device described is as a filter for frequency stabilization,
25 one of the articles cited, "Wide-band Optical Communication Systems, Part I - Time Division

Multiplexing", by T. S. Kinsel, Proc. IEEE, Vol. 58, Oct. 1970, pp. 1666-1683 is referenced in regard to the use of birefringent optical filters to multiplex or demultiplex carriers of different frequencies in the field of wide-band optical communications.

A usage of crystals that is somewhat more related to the interleaving filter context is disclosed in a letter published in Electronics Letters, Vol. 23, No. 3 dated 29 Jan. 1987, at pp. 106 and 107, by W. J. Carlsen et al, discussing the use of a series of birefringent crystals configured to improve the characteristics of systems disclosed by articles on prior tunable multiplexer/demultiplexers (referenced therein). All of these multiplexers are intended to be used with either of two lasers about 15 to 25 nm apart in optical wavelength, but they do not suggest features suitable for an interleaving function or operation at the now common 100 to 200 GHz spacings. A 100 GHz interleaving filter, for example, requires a passband of the order of 0.2 nm (vs. about 10 for the Carlsen et al system) and like intermediate stop bands. Carlsen et al do discuss a modification which achieves a flattened passband using five retardation plates of selected orientations relative to the end polarizers, and achieving polarization independence by splitting the beam so as to direct polarization components separately through the filter.

A need thus exists for a wideband interleaving filter having multiple narrow channel spacings and functioning with wide and flattened passband characteristics, insensitivity to polarization, temperature stabilization and very low insertion loss. The need includes a configuration made of readily available materials that can be readily assembled with the necessary precision, and that is of compact size and also mechanically stable.

Summary of the Invention

Interleaving circuits for optical networks in accordance with the invention utilize a series of birefringent crystals in varying electrooptic property combinations and orientations to provide densely packed periodic transmission peaks which nonetheless have very low insertion loss,

polarization independence, flattened passband peaks and temperature compensation. Pairs of dissimilar birefringent elements in cascaded (series) relationship broaden the transmissive peaks while compensating out the effects of temperature variations. By mounting the elements on a planar reference structure having preset recesses in which adjustments can be made, the unit can
5 be aligned and adjusted with respect to retardation, spacings and orientation for best performance.

In a more specific example of an interleaving filter in accordance with the invention, birefringent crystals are arranged in series between an input and output beam displacing polarizers, together with beam combining elements at the output. The input beam is divided into two beams of orthogonal polarization, which are successively incident on two stages of paired
10 birefringent crystals, the crystals of each pair being of opposite sign of thermo-optic coefficient and of specific length ratios, and the crystals of the second pair being twice the length of the first. With crystals of yttrium orthovanadate (YVO_4) and lithium niobate (LiNbO_3), respectively, the ratio used is 6.60 to 1, and the crystals are precisely spaced apart and provided with anti-reflection coatings on the beam-incident surfaces. The lengths used are inversely related to the
15 desired channel spacing. The optical (c) axes of the crystals are angled relative to the polarized input signals and to each other to utilize the retardation difference of the birefringent crystals, providing two temperature compensated output beams having flatband maxima, which are then split into another set in an output beam splitting polarizer. One combined beam of both polarization components is collimated for direction to one output fiber, while two separate beams
20 of orthogonal polarization are combined in a group of prisms and a polarizing beam splitter cube, for direction through a collimator to a second output fiber.

This interleaving filter, enclosed in a sealed housing, is less than 20 cm^2 long and 5 cm^2 wide. Placement and angular orientation of the optical elements is facilitated by the shaping of receiving recesses in the optical bench, along the optical beam path. Where a pyroelectric crystal
25 such as LiNbO_3 is used, buildup of surface charges due to temperature cycling is avoided by

current conduction from the crystal faces that do not receive the optical beams. To achieve precise tuning, crystal faces may be angled so that relative translation of beams with respect to the crystals changes the path length within crystals.

In accordance with other features of the invention, beam displacing polarizers are used in recombination of beams which have passed through the birefringent crystal system. Path length differences can be equalized by employing a half wave plate in both beams or a compensating plate in one of the beams incident on the beam displacing polarizer.

Brief Description of the Drawings

A better understanding of the invention can be had by reference to the following description, taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a somewhat simplified perspective view of an example of an interleaving optical filter in accordance with the invention;

Fig. 2 is a schematic side view representation of the filter of Fig. 1 within a housing;

Fig. 3 is a schematic perspective representation of the orientation of crystals and polarizers in the filter of Figs. 1 and 2, and an optical bench on which they are mounted;

Fig. 4 is a simplified plan view of the filter of Figs. 1-3, illustrating beam paths along the structure;

Fig. 5 is a waveform diagram showing the periodic characteristic of a 100GHz interleaving filter with passband flattening;

Fig. 6 is a waveform diagram of characteristics of a series of birefringent crystals, showing passband flattening;

Fig. 7 is a simplified block diagram view showing further features as to interleaving filter design and construction;

Fig 8 is a simplified block diagram view showing further features as to interleaving filter design and construction, and

Fig 9. is a simplified block diagram view showing further features as to interleaving filter design and construction.

Detailed Description

5 Birefringent or polarization filters are described in "Optical Waves in Crystals", Yeh and Yariv, referenced above. The transmission through a birefringent element sandwiched between parallel polarizers is periodic in frequency and is given by:

$$I(\lambda) := \left[\cos \left[\pi \cdot \frac{(n_e - n_o)}{\lambda} \cdot L \cdot 10^6 \right] \right]^2 \quad \text{Eqn. 1}$$

10 where I is the intensity, λ is the wavelength in nanometers, n_e is the extraordinary index of refraction, n_o is the ordinary index of refraction and L is the thickness of the crystal in mm. The crystal is oriented with its optic axis at 45 degrees to the input polarization. Note that in this governing relationship the transmission is periodic in optical frequency (i.e. inverse wavelength) and the transmission is lossless at the peak. The present systems use this fundamental controlling

15 Eqn. 1 together with a number of others in providing shaped transmissivity characteristics with low insertion loss, polarization insensitivity and compensation for temperature variation.

Figs. 1 to 4 depict the arrangement and relationships of the components of a 1x2 passband flattened and temperature compensated interleaving filter 10, the components of which are seated on a generally planar surface 13 of a stainless steel optical bench 12 (see Figs. 2 and 3). The

20 optical bench 12 (which alternatively can be of other materials such as silicon) contains shaped recesses 14 formed by electron discharge machining (EDM), in which recesses 14 in the planar surface 13 the polarizing components and crystals are mounted and precisely aligned and angled. A gradient index (GRIN) lens responsive to the wideband input stream from an optical fiber is a collimator 16 for the WDM channel stream. The collimator lens 16 is secured within a cylindrical

metal housing 20 which is welded within a stainless steel clip 22 of general U-shape, where base legs 24, 25 are welded to the optical bench 12. The clip 22 design allows for precise and stable tilt and translation adjustment of the collimator lens during assembly.

After collimation, the input beam is transmitted through a beam displacing polarizer 28, here of YVO4 crystal, which splits the input beam into two parallel beams (Fig. 4 particularly) with crossed polarizations that are shifted 1mm with respect to the other. Splitting the input beam into separate polarizations and then recombining after filtering results in a polarization independent device.

The two beams are then incident on a first birefringent crystal stage comprised of a yttrium orthovanadate (YVO4) crystal 30 and a Lithium niobate (LiNbO₃) crystal, 32 configured to form a first a temperature compensated pair. There are a number of different birefringent materials which can be used for temperature compensation, including YVO4 and LiNbO₃. YVO4 has high birefringence, $\Delta n = 0.2039$ at 1550nm, and is readily available commercially. LiNbO₃ has a large thermooptic coefficient opposite in sign to YVO4 and is also readily available commercially. The required length ratio for temperature compensation of YVO4 to LiNbO₃ is 6.60:1. The lengths scale inversely with channel spacing, and 50GHz and 25 GHz spacing are achievable. The optical (C) axis of the YVO4 crystal and the LiNbO₃ crystal 32 are oriented at 45° relative to the input polarizer 28. For a 100GHz to 200GHz channel spacing the YVO4 crystal 30 is 7.370 mm long and the lithium niobate crystal 32 is 1.116 mm long.

The second stage, which is also temperature compensated but employed to flatten the peak of maximum transmissivity of the passband is comprised of another set of YVO4 36 and lithium niobate crystals 38. The lengths of each of these are twice that of the like crystals used in the first stage. The optical axes of each separate crystal 36,38 of the second pair is oriented along a crystal edge and the crystals are tilted -14.8 degrees with respect to the top surface 13 of the optical bench 13. The edges of the lithium niobate crystals 32 and 38 are electrically shorted with a

conductive coating 40 such as silver epoxy which conducts away charges built up due to the pyroelectric property of LiNbO_3 . Such electric charges would otherwise tend to build up on the surface of crystals 32, 38 as the temperature is cycled, and the result could be uncontrolled hysteresis of the index of refraction. Such charges must be eliminated for LiNbO_3 to be used as a temperature compensating element. Conductive silver epoxy 40 (or metallization or anti static liquid) of the +/- c faces of a crystal electrically shorts the crystal and dissipates charges. Dopants such as MgO which reduce the electrical conductivity would also reduce the pyroelectric effects.

The two beams after being transmitted through the birefringent crystals 30, 32, 36, 38 are incident on another YVO4 beam displacing polarizer 41. Each input beam is split up into two beams with different polarizations, as best seen in Fig. 4. Two of the beams with crossed polarization overlap and are coupled directly into one of two output GRIN lens collimators 46, 48. The two other beams are combined in part by using a single prism 42 to direct the s polarized beam to one side of a polarizing beam splitter cube, 43 with the p polarized beam being redirected off a pair of prisms 44, 45 to an orthogonal side of the beam splitter cube 43. The path lengths of the two combined beams are matched to better than 1mm in order to minimize polarization mode dispersion (PMD). The resulting overlapping beams are then coupled into the second output collimator 48. The output collimators 47, 48 are laser welded to clips which are in turn laser welded to the optical bench 12.

Referring specifically to Fig. 2, the optical bench 12 is mounted inside a tray 50 with a fiber feedthrough 52 in the end wall 54 receiving an input optical fiber 18 in line with the input collimator 16. Although the output side is not shown in this view it differs in having only pairs of elements for delivering the two output beams. The bench 12 is attached to the base of the tray 50 with RTV adhesive or, as shown, a silicone sheet 58 can be used to provide cushioning from shock and vibration. The input fiber 18 and two output fibers are fed through the fiber

feedthroughs and sealed with epoxy. A lid 58 is attached to the body of the tray 50 and the waist is sealed with epoxy in a dry nitrogen atmosphere.

All of the optical surfaces, including the crystals, are antireflection coated to minimize optical loss.

5 The experimentally measured transmission (using an LED and an optical spectrum analyzer) of a fiber coupled, passband flattened 100Ghz interleaver is shown in Figure 5. The unit uses two stages of lithium niobate and YVO4 crystals. This measured response is charted in Fig. 5. The spacing between transmissivity peaks is that of a 100Ghz channel spacing to 200Ghz channel spacing interleaving filter.

10 Wider passband flatness in a filter (i.e. a broadening of the width of the transmissivity peaks, prevents narrowing of the transmission spectra when filters are cascaded and reduces the required wavelength accuracy of the WDM source lasers. It also improves system performance by reducing the attenuation of the information content of a modulated signal. By adding additional birefringent elements, the passband of the interleaving filter is flattened to a selectable
15 degree. As shown in Fig. 6, which depicts response variations between one, two and three crystals in series the passband of a single element birefringent filter is 0.35nm wide at the -0.5dB bandwidth. By adding a second and third birefringent element, shown by dotted and dashed lines respectively, the maximum is progressively broadened. The first element is of length L and oriented with its C axis at 45 degrees. For a series of two, the second element is of length $2L$ and
20 has an orientation of -14.8 degrees, substantially widening the amplitude at maximum without broadening the cutoff point. Addition of a third element of length $2L$ and orientation $\approx +10$ degrees broadens the maximum even further, but introduces intermediate dips of minor magnitude. For a 100Ghz /200ghz interleaver the bandwidth for a passband flatness of -0.5dB is 0.35nm for the single stage, 0.47nm for the two stage, and 0.60nm for the three stage design.
25 Even better flatness can be achieved by adding more elements, however this comes at the expense

of additional cost and insertion loss. Although the curves depict the results of measurements with crystals of only one type, they are equally valid for temperature compensated combinations using different crystal types.

The polarization dependent loss (PDL) of the interleaving filter must be minimized to a value below 0.1dB. This is achieved during coupling of the two crossed polarization beams incident on each output GRIN lens collimator 46 or 48. In order to minimize PDL the beams must be coupled into the output fiber with the same efficiency. This is not necessarily at the peak coupling efficiency of each beam. This can be determined by varying or switching the input polarization to the interleaving filter 10 until no variation of power on the output fibers is measured.

In order to make a polarization independent fiber based interleaving filter, the signal is split up into two beams using the lossless beam displacing polarizer 28. The two beams are transmitted through the birefringent elements 30, 32, 36, 38 and recombined into two outputs using the additional lossless beam displacing polarizer 42. The s polarized output of one of the beams is recombined with the p polarization of the other beam. Every other channel of a WDM stream is thus separated into one of the two output collimators 46, 48 and the output fibers to which they couple.

Devices typically operate over a 0-70C temperature range and should be passively temperature compensated. For a 100Ghz filter response the center wavelength drift should typically be less than +/-0.0015nm/C. The use of different crystals with opposite signs of the birefringence or thermooptic coefficient in the manner described achieves this result. The retardance of two crystals in series is given by:

$$\Gamma_1 + \Gamma_2 := \frac{2 \cdot \pi}{\lambda} \cdot (L_1 \cdot \Delta n_1 + L_2 \cdot \Delta n_2)$$

Where Γ is the phase retardance, L is the length of each crystal, and the birefringence is given by $\Delta n_1 = n_{e,1} - n_{o,1}$ for the first crystal. For the second crystal $\Delta n_2 = n_e - n_o$ if the crystal axis is parallel to that of the first crystal and is $\Delta n_2 = n_o - n_e$ if it is rotated 90 degrees. The change of retardance with temperature is given by:

$$\frac{d(\Gamma_1 + \Gamma_2)}{dT} := \left(\frac{2\pi}{\lambda} \right) \left(L_1 \frac{d(\Delta n_1)}{dT} + L_2 \frac{d(\Delta n_2)}{dT} + L_1 \alpha_1 \Delta n_1 + L_2 \alpha_2 \Delta n_2 \right)$$

5

Where α is the thermal expansion coefficient. The condition for compensation is given by:

$$\frac{L_1}{L_2} := \frac{-\left(\frac{d(\Delta n_1)}{dT} + \alpha_1 \Delta n_1 \right)}{\left(\frac{d(\Delta n_2)}{dT} + \alpha_2 \Delta n_2 \right)}$$

Usually the thermal expansion coefficient term can be neglected. With the optic axis of the crystals in alignment, compensation is achieved using two crystals with different signs of the thermooptic coefficient. If the crystals are rotated 90 degrees with respect to each other, materials
10 can be used with the same sign of the thermooptic coefficient.

During assembly, both the frequency period and absolute wavelength of the peaks must be adjusted. This can be controlled by tight tolerances of the thickness of the polished crystals. The crystals or the input beam angle can also be tilted to adjust the wavelength. Another approach is
15 to polish the crystal to form a slight wedge shape, with the beam-incident faces thus being non-orthogonal to beam direction. Then the wavelength and period can be adjusted by translating the beam on the crystal. In order for both the parallel beams to see the same thickness of crystal, the wedge angle should be transverse to the plane of the two incident beams. Two crystals with opposing wedges can be translated relative to each other to adjust the thickness and minimize any
20 beam steering. Another approach to tune the wavelength is to choose from a set of LiNbO₃

crystals at slightly different thickness, and tuning by substituting for the best response. A spacing of 10microns can allow for tuning while only slightly changing the temperature compensation condition. Adjustment of the absolute wavelength peaks of the filter can also be achieved by using a zero order half wave plate after each of the stages. By rotating the waveplates additional
 5 birefringence is introduced which tunes the filter. Zero order waveplates are used to minimize temperature dependence of the waveplate.

The alignment and tolerance of the optical components are critical. Both insertion loss and manufacturing assembly cost need to be minimized. An alternative to the stainless steel optical bench is to use a silicon bench as a platform to mount all of the components. Precise V-
 10 grooves are etched onto the silicon substrate and components are dropped into them and attached with epoxy.

1x2 interleavers can be cascaded to split every Nth channel into one of N output fibers. For the second stage a crystal of half the thickness of the first stage is required. In general the transmission through an N stage interleaver will have a transmittance at one of the output fibers
 15 given by:

$$I(\lambda) := \prod_{i=1}^N \left[\cos \left[\pi \cdot \frac{(n_e - n_o)}{\lambda} \cdot \frac{L}{i} \cdot 10^6 \right] \right]^{2 \cdot i}$$

The other fibers will have the same wavelength dependent transmittance with the peaks shifted by a multiple of the input channel spacing.

20 Each stage of a birefringent filter is not limited to separating every other channel. More generally a single stage can group every Nth channel onto a single fiber and the remaining (N-1) adjacent channels in each period onto a separate fiber. One approach is to use a Solc type filter

described in the Yeh and Yariv treatise referred to above. There are two designs, folded and fanned, which rely on a stack of rotated birefringent plates of equal thickness.

Another example of an arrangement in accordance with the invention, referring now to Fig. 7, divides the input beam from an input collimator 60 into an s polarized beam and an
5 orthogonal p polarized beam at a first beam splitting polarizer cube 62. The p polarized beam is directed back into parallelism for compactness at a prism 63, and both beams then pass separately through sheet polarizers 64, 65 to temperature compensating birefringent crystal pairs 70, 71 and 73, 74 as described above, after which separate beam pairs are recombined. S polarized components are angled off a prism 80 to one face of a second polarizer cube 82, which receives
10 the p polarized beam at another face. From the second cube 82 two orthogonal beams merge, each combining s and p components, and the two combined beams are directed to first and second collimators 84, 85 respectively. This arrangement simplifies beam recombination but, because of the characteristics of polarizing beam splitters the cross-talk between adjacent channels is higher, even though reduced somewhat by the sheet polarizers. In addition, the costs of using separate
15 crystals of equal lengths must be considered.

Other examples of arrangements in accordance with the invention, referring to Fig 8 and Fig 9 make use of different optical arrangements to recombine the s and p polarized beams into the second output fiber. In Fig 8 the optical layout from the input collimator through the birefringent crystals and the second beam displacing polarizer is the same as described previously.
20 Here, however, a prism 90 is used to pick off the center beam emerging from the second beam displacer 41 which contains both required polarizations. This beam is reflected with another prism 92 and coupled directly into an output collimator 47. The other two beams emerging from the second beam displacer 41 are recombined within a third beam displacing polarizer 94. The length of the last beam displacer 90 is twice that of the first two 28, 41 due to the need for twice
25 the displacement. Since the path lengths of the two beams would not otherwise be matched, a

compensating plate 96 is inserted in one of the beam paths to match the optical path length. A high index material such as lithium niobate, with the crystal axis aligned with the input polarization, is used in the s polarized beam.

Another approach to match the optical path lengths is shown in Fig 9. The two beams
5 emerging from the second beam displacer 41 are transmitted through a half wave plate 98 and then recombined using a third beam displacement polarizer 100. The half wave plate 98 rotates the polarizations 90 degrees, which ensures that the overall path lengths of the two beams are matched after going through the final beam displacer 100. The half wave plate 98 is a zero order
10 second beam displacing polarizer 41 are angled off a common prism 102 to the second output collimator 48.

Although a number of variants and alternatives have been described, the invention is not limited thereto but encompasses all forms and modifications within the scope of the appended claims.

CLAIMS:

1. An interleaving optical filter for wave energy, for providing a periodic low loss
5 transmissivity characteristic in the rate of 25 GHz to 200 GHz spacing and operating with
substantial polarization independence and with compensation for temperature variations, said
filter comprising:
- a support providing a generally planar surface extending substantially parallel to a
principal optical axis for the filter;
- 10 an input collimator mounted on the support at an input region thereon to provide a
collimated beam along the principal optical axis;
- a first beam displacing polarizer mounted on the support to receive the collimated
beam, the polarizer transmitting two beams of orthogonal polarization that are parallel to the
principal optical axis;
- 15 a first pair of birefringent crystals receiving the two beams and being of different
thermooptic coefficients and with lengths along the principal optical axis that are selected to
compensate for temperature-induced phase retardation variations, the first pair being rotated 45°
with respect to the planar surface about the principal optical axis.
- a second pair of birefringent crystals of materials like the first pair but of different
20 length, and being rotated with respect to the planar surface to provide transmissivity peaks that
have passband flatness of -0.5dB of about .47 nm and a center wavelength drift of less than
 $\pm 0.0015 \text{ nm}/^\circ\text{C}$;

a second beam displacing polarizer receiving the two beams transmitted through the pairs of birefringent crystals for splitting each of the two beams into two beams with different polarizations, and

a beam recombining unit receiving the beams from the beam displacing polarizer
5 for combining the beams therefrom into two polarization independent beams in the component beams with less than one 1 mm path length difference.

2. An interleaving optical filter as set forth in claim 1 above, including output collimators coupled to transmit the different polarization independent beams.

3. An interleaving optical filter as set forth in claim 1 above, wherein the second
10 beam displacing polarizer transmits a pair of orthogonally polarized individual beams and a combined beam having orthogonally polarized components, and the beam recombining means directs the combined beam as one of the outputs.

4. An interleaving optical filter as set forth in claim 3 above, wherein the beam recombining means includes a third beam displacing polarizer receiving the orthogonally
15 polarized individual beams, and further includes a path length compensator in one of the beam paths to the third beam displacing polarizer.

5. An interleaving optical filter as set forth in claim 3 above, wherein the beam recombining means includes a third beam displacing polarizer receiving the orthogonally polarized individual beams, and further includes a half wave plate in both beam paths to the third
20 beam displacing polarizer.

6. An interleaving optical filter as set forth in claim 3 above, wherein the beam recombining means comprises a polarizing beam splitter cube and prism means for directing the orthogonally polarized individual beams to different faces of the beam splitter cube.

7. An interleaving optical filter as set forth in claim 1 above, wherein the birefringent crystals are of opposite sign, and wherein the second pair of crystals have a negative angular rotation relative to the first pair.

8. An interleaving optical filter as set forth in claim 1 above, wherein the pairs of
5 birefringent crystals each comprise a YV04 crystal and an LiNbO₃ crystal having length ratios of 6.60:1 and wherein the crystals of the second pair are twice the length of those in the final pair.

9. An interleaver filter as set forth in claim 1 above, wherein the first and second beam displacing polarizers are of YV04 crystal and the beam recombining unit comprises a prism and polarizing beam splitter cube.

10. An interleaving optical filter as set forth in claim 2 above, wherein the input
10 collimator and output collimators comprise gradient index lenses, wherein the filter further includes housings attached to the collimators and the housings are attached to the support, wherein the collimators are disposed along the principal axis, and the filter further comprises input and output optical fibers in communication with the input and output collimators
15 respectively.

11. An optical assembly for retaining a number of birefringent elements, polarizing elements and collimating elements in precise axial and rotational positions along an optical axis, comprising

an optical bench having a principal planar surface, the surface including inset
20 recesses disposed at spaced locations along the length of the optical axis; the recesses having angles relative to the planar surface to define the rotational orientation of the birefringent elements;

adjustable attachment mechanisms attached to the optical bench at collimator positions along the optical axis,

collimator housings each supporting a different collimator and each attached to a different one of the attachment mechanisms.;

and a containment housing encompassing the optical assembly and including optical fiber feedthroughs along the optical axis and in alignment with collimating elements therein.

12. An optical assembly in accordance with claim 11 above, wherein the optical bench is of stainless steel, and wherein in addition to the attachment mechanisms are laser welded to the optical bench and at least one of the birefringent elements are conductively coupled to the optical bench.

13. An optical assembly in accordance with claim 12 above, wherein the housing includes a tray and a lid in a sealed configuration, and a layer of resilient material supporting the optical bench in the tray.

14. An interleaving optical filter for introducing a periodic transfer function with flattened apices within transfer in a wider band spectrum of an input optical beam, comprising;
a first polarizer in the path of the input optical beam;
at least two stages of pairs of birefringent crystals of opposite thermo-optic coefficients, the crystals of each pair having a like length proportionality but the lengths of the crystals in the first pair having a selected ratio to the lengths of the crystals of the second pair, the longer pair being disposed closer to the first polarizer, and

a second polarizer in the path of the optical beam subsequent to the two stages.

15. An optical filter as set forth in claim 14 above, wherein the like crystals within each stage have like optical axes and orientations relative to the polarizer direction and wherein the filter further includes beam displacing means between the first polarizer and the at least two stages for directing beams of orthogonal polarization through the at least two stages, and wherein

the filter further includes an optical circuit for recombining the beams of orthogonal polarization into two beam sets, each including both polarizations.

16. An optical filter as set forth in claim 15 above, wherein the lengths of the crystals are selected to provide a selected periodicity in the transfer function, and wherein the optical
5 circuit recombines the beams in the beam sets with equal path lengths.

17. An optical filter as set forth in claim 16 above, wherein each pair of crystals comprise a YVO4 crystal and an LiNbO₃ crystal, and wherein the C axes of the first pair are at 45° to the direction of the first polarizer and the C axes of the second pair are at $\square 14.8^\circ$, and wherein the length proportionality of the crystals in each pair is 6.60:1 and the ratio between the two pairs
10 is 1:2.

18. An Optical filter for introducing an interleaving function into a signal beam occupying an optical band, comprising:

a polarizing beam splitting cube for dividing the signal beam into two orthogonally polarized beams;

15 first and second birefringent crystal sets, each including an initial polarizer sheet and two pairs of serially disposed birefringent crystals of opposite thermooptic sign, and

beam recombining means including a second polarizing beam splitting cube receiving the two orthogonally polarized beams and providing two output beams, each including both polarization components.

20 19. A filter for separating an input band of optical signal frequencies into a number of periodicity varying transmissive frequency bands divided into at least two groups, comprising:

at least one pair of birefringent crystals disposed serially along an optical axis for receiving the optical signals, at least one of the crystals having a pyroelectric characteristic;

polarizing means disposed along the optical axis and bordering the at least one pair of optical crystals, and

means coupled to crystals having a pyroelectric characteristic for dissipating electric charges induced thereon.

5 20. A filter as set forth in claim 19 above, wherein the crystals of a pair have optical axes that are similarly aligned relative to the optical axis of the device, and wherein the polarizing means comprises a beam displacing polarizer for dividing the optical signals into two beams directed along the optical axis.

10 21. A filter as set forth in claim 20 above, wherein the at least one pair of birefringent crystals comprises two pairs, the second pair having alignments of their optical axes that are alike within the pair but different from the other pair, and have a selected length relationship to the crystals of the other pair.

 22. A filter as set forth in claim 19 above, wherein the means for dissipating electric charges comprises conductive coating material disposed on selected surfaces of the crystals.

15

23. An optical filter for transferring optical signals in either direction between a terminal at one side and a pair of terminals at the other side, in either direction, the optical signals periodically spaced in wavelength, the filter transferring the signals with a selected periodic passband function, comprising:

20

at least two serial stages of birefringent light propagating elements arranged to provide differential retardations between orthogonal polarization components of the optical beams, each stage being configured with at least two elements of different thermooptic characteristics to be substantially athermal over a selected temperature band, the differential

retardation relationships being selectively varied between the stages to provide selected passband widths at the selected passband periodicity,

at least one polarization responsive beam path juncture device between the terminal at one side and the at least two stages and transferring optical signals therebetween, splitting the signals in the beam path in accordance with polarization in one direction, and combining the signals transferred in the other direction; and

at least two beam path juncture devices each between the terminal of a different one of the pair of terminals and the at least two stages for processing optical signals therebetween, said beam path juncture devices being polarization responsive and disposed in series, and including elements arranged to cross-combine signals of orthogonal polarization, such that the filter is polarization insensitive.

24. A filter as set forth in claim 23 above, wherein the light propagating elements are arranged in two sets of at least two stages disposed in separate paths, and like elements in the parallel paths are of matched lengths and thermo-optic characteristics.

25. A filter as set forth in claim 23 above, wherein the filter further includes separate lens collimators at the outputs of the separate ones of the at least two beam path juncture device, and means associated with the at least one beam path juncture device for establishing the input polarizations of the beams to minimize the polarization dependent loss to below 0.1 dB.

26. A filter as set forth in claim 23 above, wherein the relative angles of the fast axes of the stages are selected to vary the retardation relationships, and wherein the filter includes elements for equalizing the path lengths of the separate optical beams to minimize PMD.

27. A filter as set forth in claim 23 above wherein the stages have an athermal characteristic such that the center wavelength drift is less than 0.0015 nm/°C.

28. A filter as set forth in claim 23 above, wherein the athermal compensation conditions is approximately in accordance with:

$$\frac{L_1}{L_2} := \frac{-\left(\frac{d(\Delta n_1)}{dT} + \alpha_1 \cdot \Delta n_1\right)}{\left(\frac{d(\Delta n_2)}{dT} + \alpha_2 \cdot \Delta n_2\right)}$$

5 where L is the length of each crystal, Δn is the birefringence for a crystal, and α is the thermal expansion coefficient.

29. A multiplexer/demultiplexer functioning in accordance with an interleaver transfer function for processing interleaved, wavelength multiplexed signals of a first inter-channel wavelength periodicity present at one terminal and signals at half the first inter-channel wavelength periodicity present at a pair of terminals, comprising:

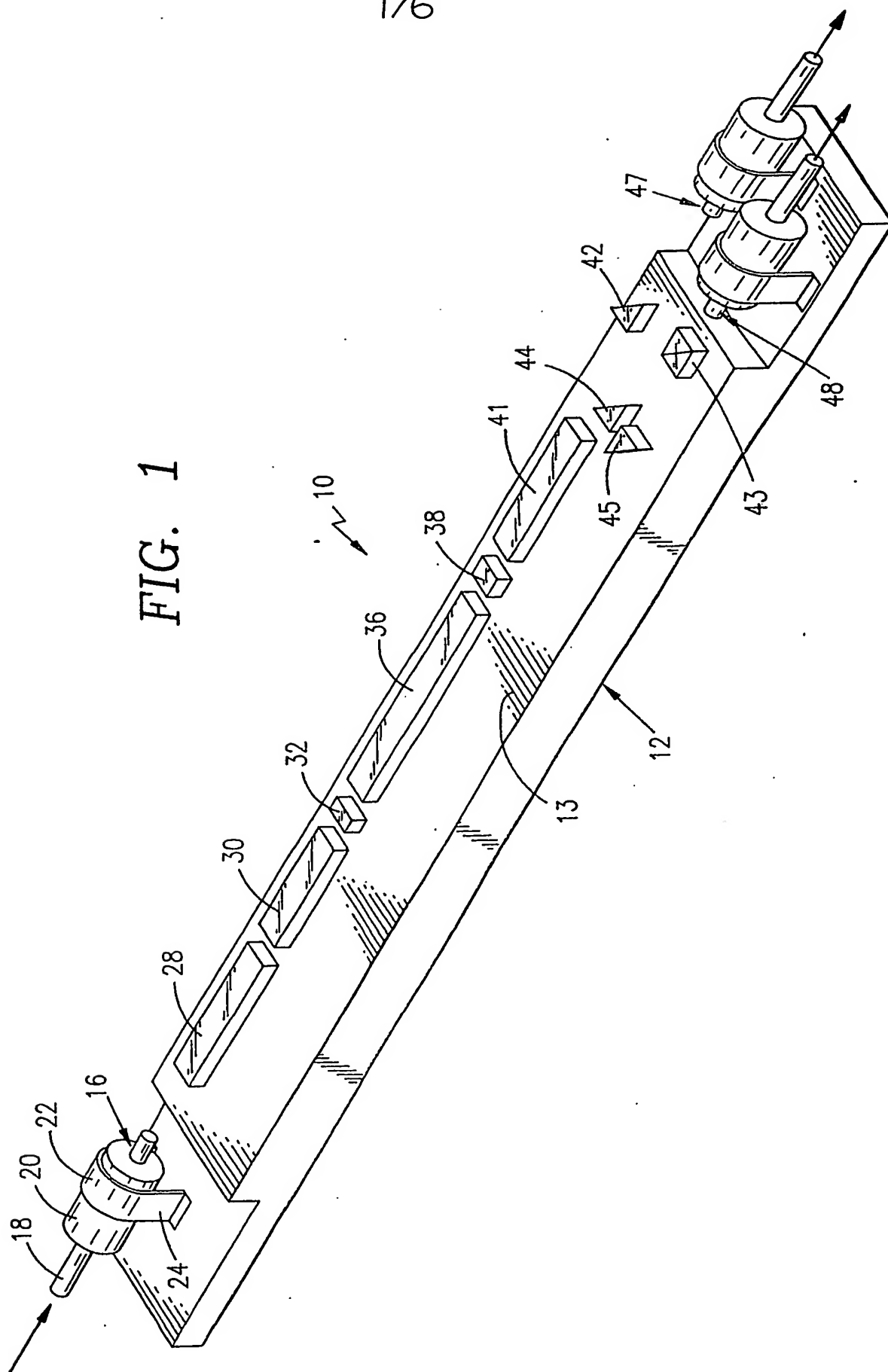
10 a pair of optical beam paths, each comprising at least two stages of optical delay elements disposed in series, each stage of each path including at least two optical elements in series, whose lengths and thermo-optic characteristics are selected to provide a differential phase retardation between orthogonally polarized beam components that is athermal over a selected temperature range to define a periodic transmission characteristic of chosen periodicity, the lengths and fast axis orientations of each stage being selected to broaden the passbands of the transmission characteristic,

15 a first beam splitter/combiner in the optical communication path between the one terminal and the pair of beam paths for (1) directing and separating received signals of arbitrary state of polarization from the one terminal into the two beam paths, the signals on the two beam paths being orthogonally polarized in a fixed relation to one another, and for (2) combining orthogonally polarized optical beams from the beam paths into signals of arbitrary state of polarization at the said one terminal, and

- a second and third beam splitter/combiner means in the optical communication path between the pair of beam paths and the pair of terminals, for (1) cross-combining orthogonally polarized beam components received from the beam paths and exhibiting periodic polarization characteristics at half the first wavelength periodicity into separate beams exhibiting periodic transmission characteristics at half the first wavelength periodicity and transferring them to the pair of terminals, and for (2) separating signals received at the pair of terminals, signals exhibiting periodic transmission characteristics at half the first periodicity, into orthogonally polarized signals, and transferring orthogonally polarized signals to the beam paths through stages as individual beams.
- 10 30. A multiplexer/demultiplexer as set forth in claim 29 above, wherein multiplexed signals applied to the terminals have arbitrary states of polarization and where the beam splitter/combiners are polarization sensitive and divide or combine beams in accordance with polarization and direction.

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FIG. 1



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FIG. 2

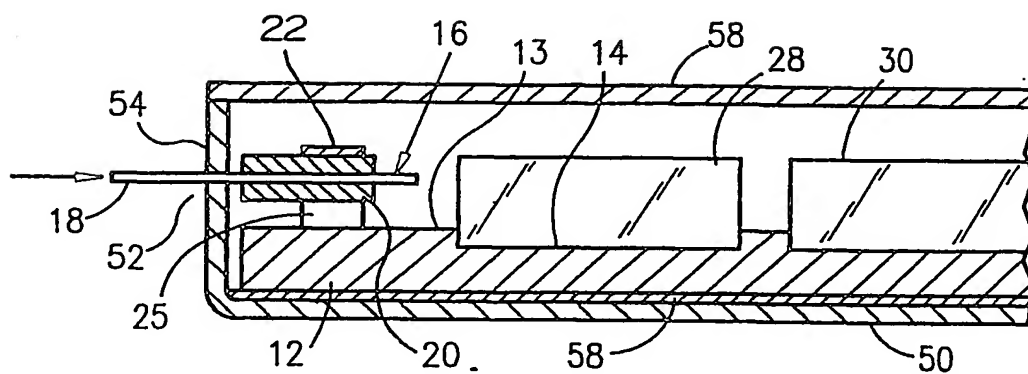
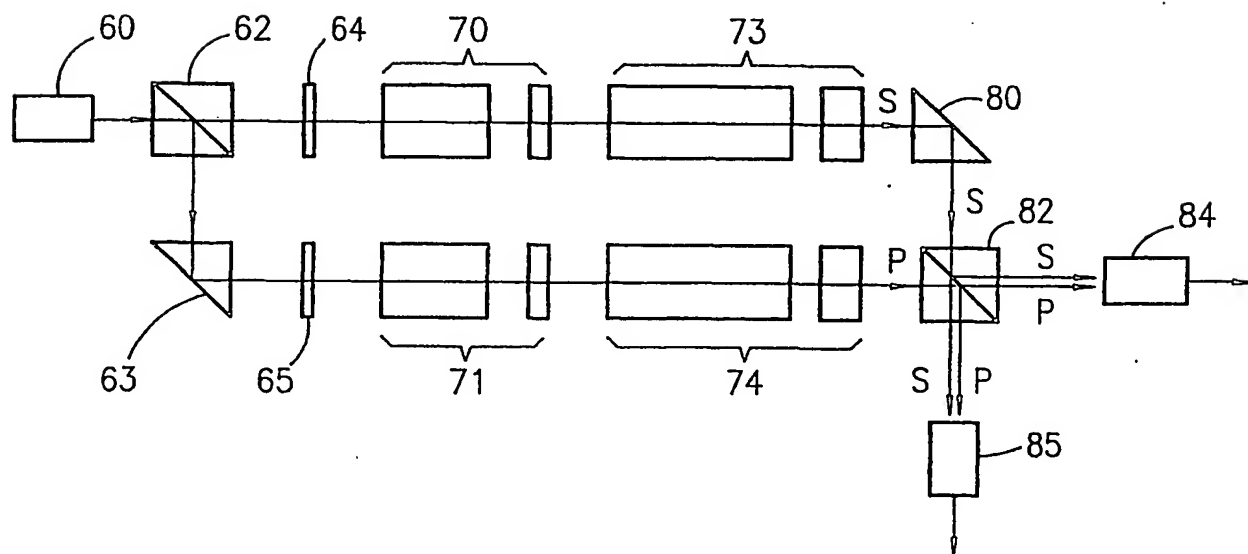


FIG. 7



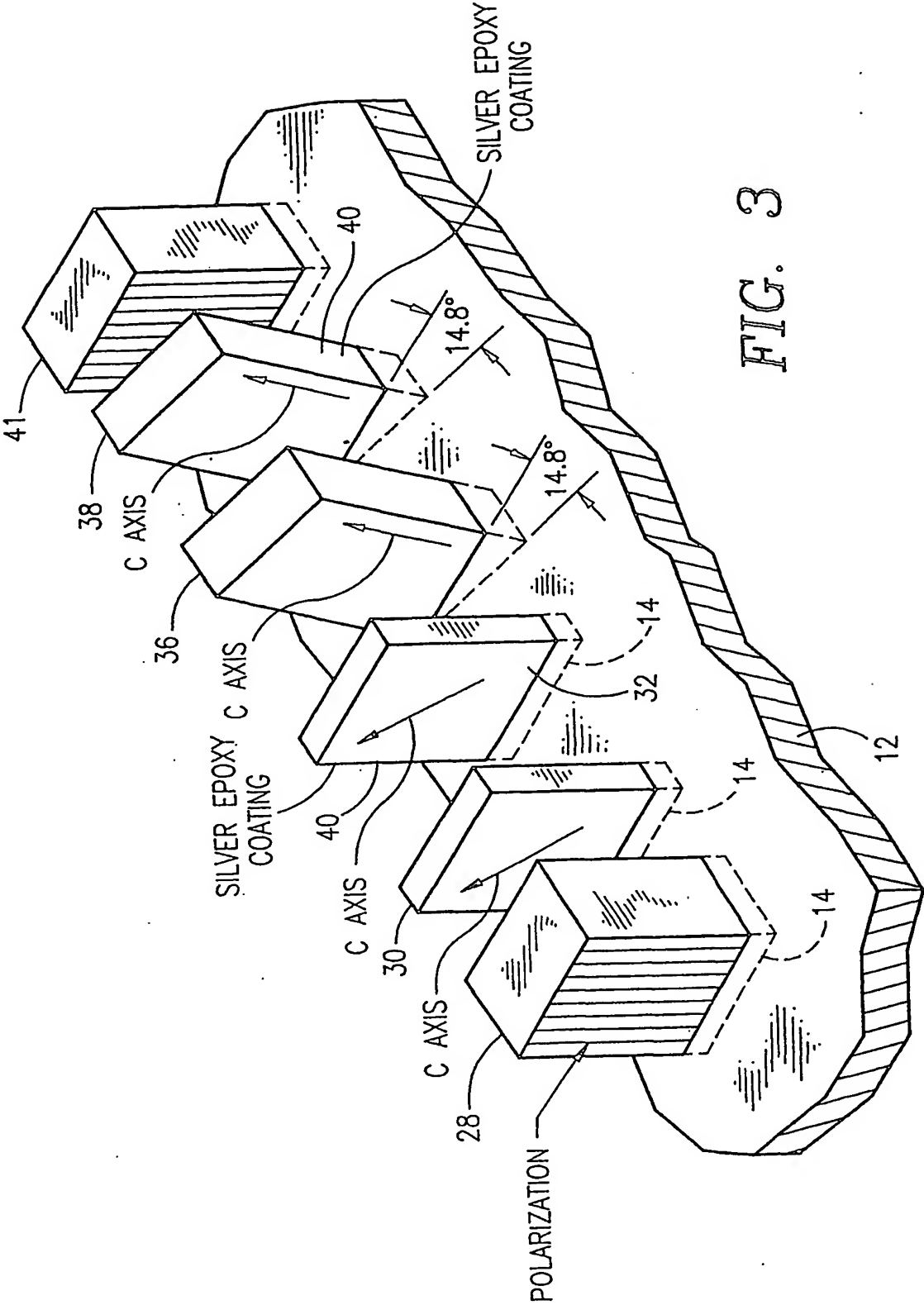


FIG. 3

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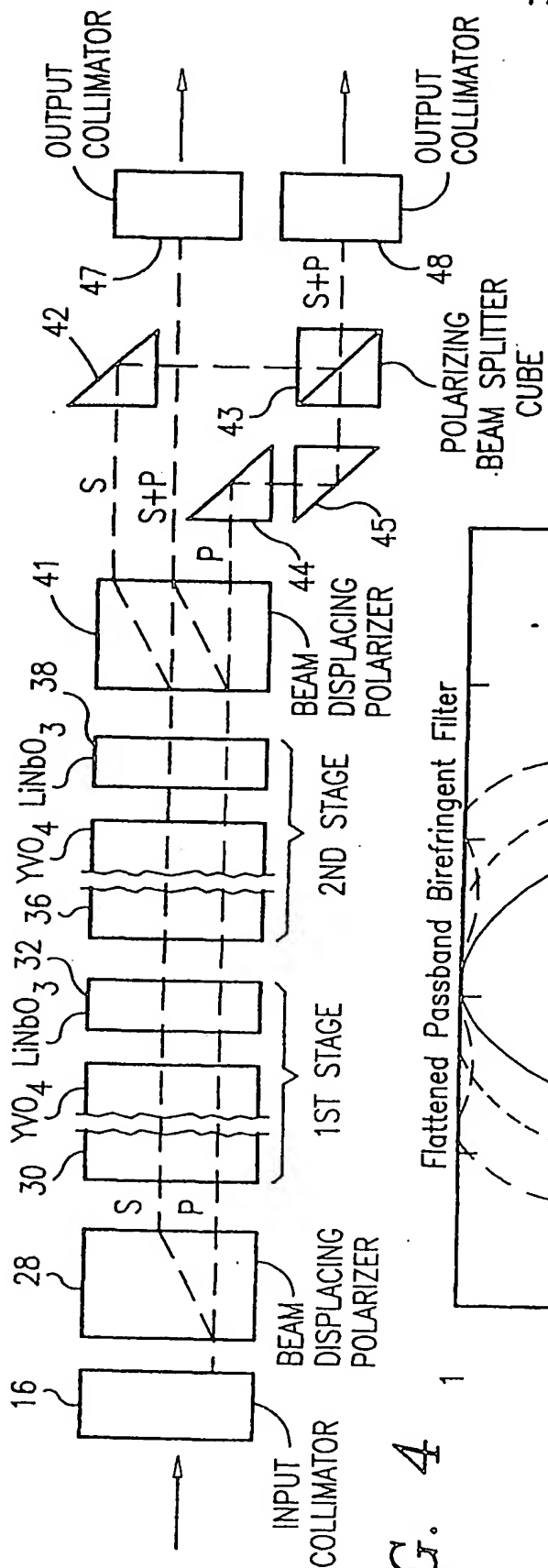


FIG. 6

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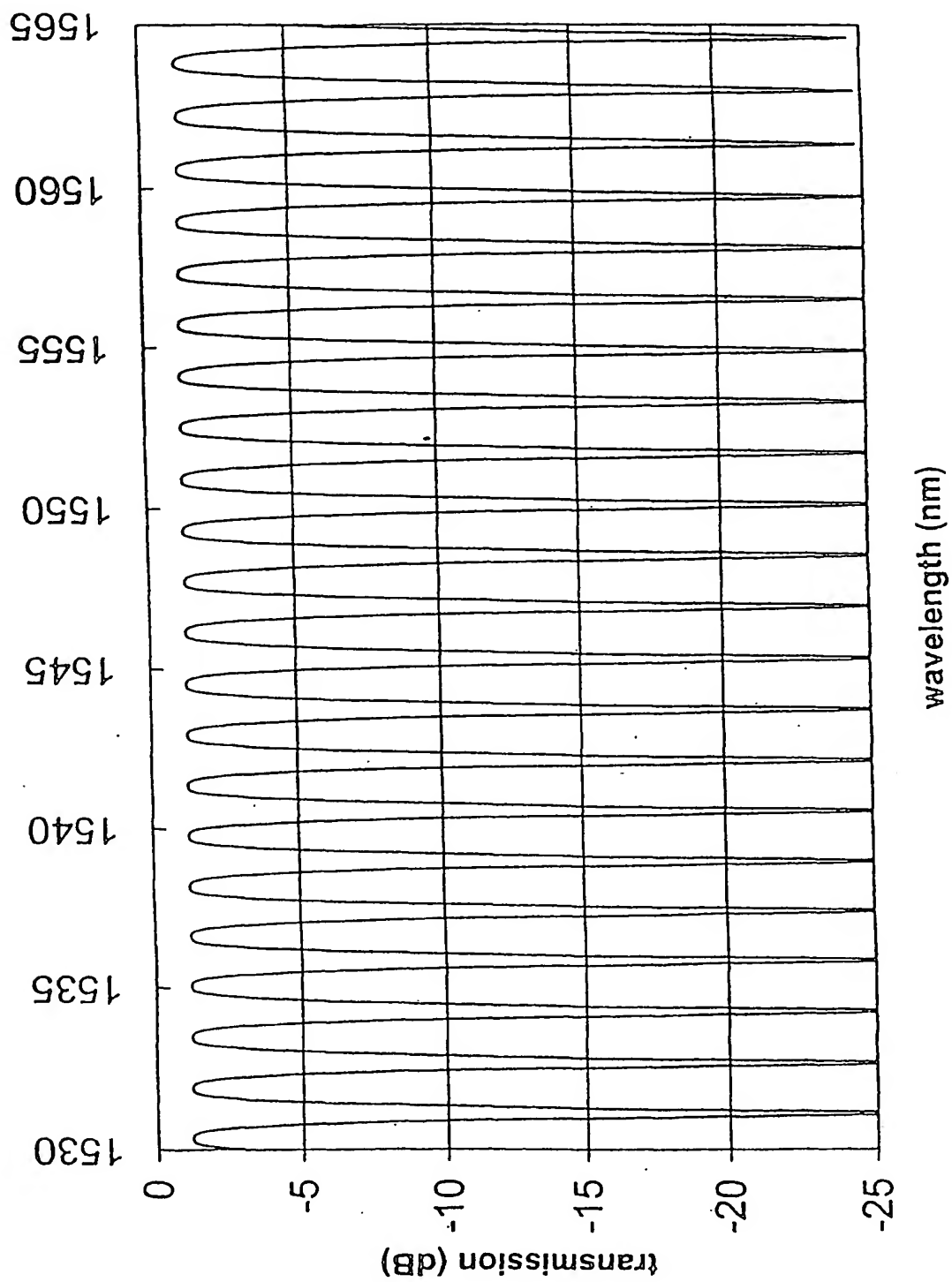
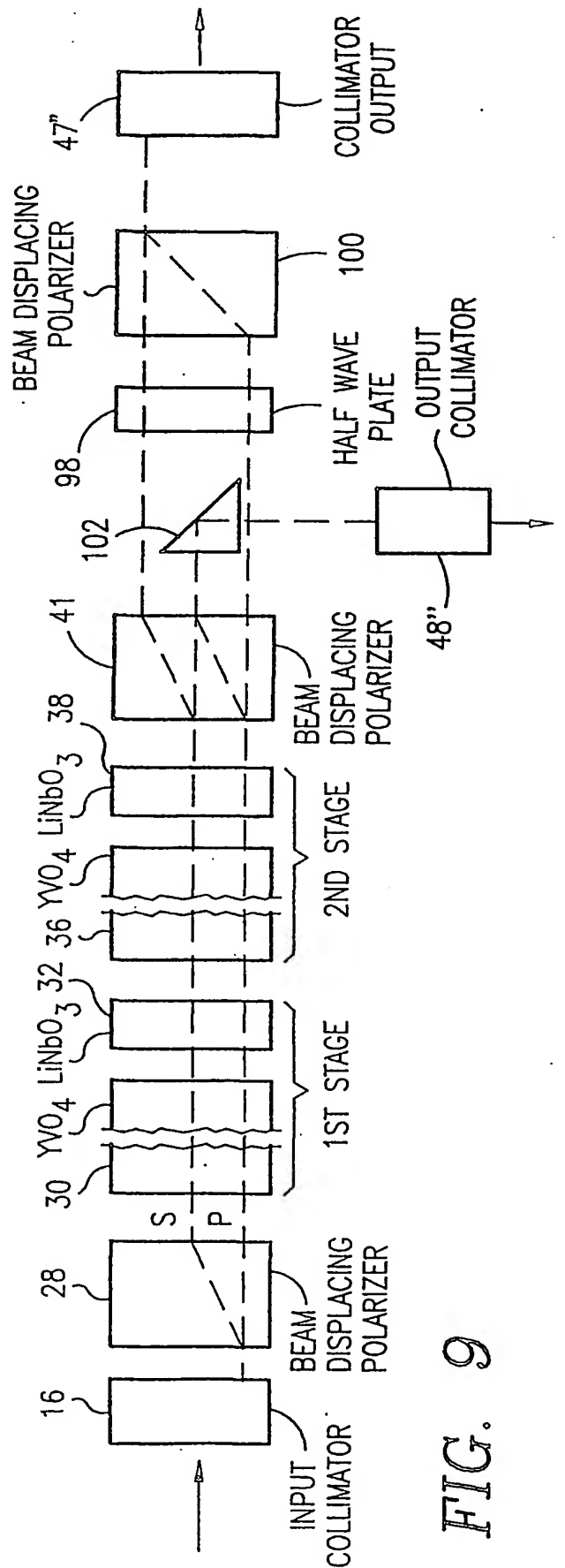
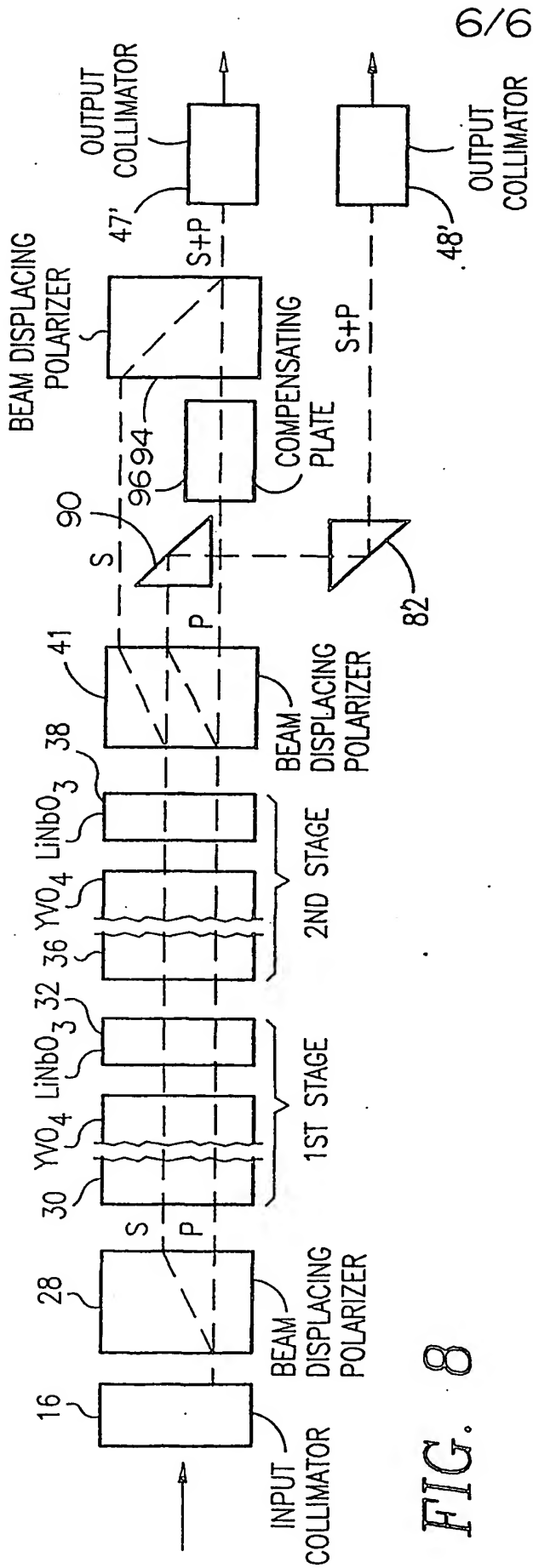


FIG. 5



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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/04935

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G02B 5/30; G02F 1/01, 1/03; H04J/ 14/02; G03B 17/50

US CL :Please See Extra Sheet.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : None

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
None

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
None

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- A	US 3,536,921 A (CAULFIELD) 27 October 1970 (27-10-70), see entire document.	14 --- 10, 15-18, 21, 23-30
X	US 3,304,428 A (PETERS) 14 February 1967 (14-02-67), see entire document.	19,20
X	US 5,305,136 A (SMITH) 19 April 1994 (19-04-94), see entire document.	19,20,22
Y	US 5,734,762 A (HO et al) 31 March 1998 (31-03-98), see entire document.	11-13
Y	US 6,028,702 A (SASAKI) 22 February 2000 (22-02-00), see entire document.	11-13

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
25 APRIL 2001

Date of mailing of the international search report

08 MAY 2001

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/04935

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,976,517 A (KOZUKA et al) 11 December 1990 (11-12-90), see entire document.	19,20,22
Y	US 4,327,971 A (KONDO et al) 04 May 1982 (04-05-82), see entire document.	19,20,22

Form PCT/ISA/210 (continuation of second sheet) (July 1998)*

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/04935

A. CLASSIFICATION OF SUBJECT MATTER: US CL :

359/124, 250, 251, 256, 259, 288, 494, 495, 497, 498;
385/11, 31, 33

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